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# Tau Jet Signals for Supersymmetry at the Tevatron

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## Abstract

We present a more detailed account of our study (hep-ph/9903238) for the supersymmetry reach of the Tevatron in channels with isolated leptons and identified tau jets. We review the theoretical motivations for expecting such signatures, and describe the relevant parameter space in the minimal supergravity and the minimal gauge-mediated models. With explicit Monte Carlo simulations we then show that for certain parameter ranges, channels with two leptons and one tau jet offer a better reach in Run II than the clean trilepton signal. We emphasize that improving on tau ID is an important prerequisite for successful searches in multiple tau jet channels. Finally, we discuss some triggering issues.

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# 1 Introduction and Motivation

No matter how one looks at it, the third generation in the Standard Model (SM) is special. (The 3rd generation fermions may provide a clue to the origin of mass, fourth generation, etc.) This is even more so in the Minimal Supersymmetric Standard Model (MSSM), where the third generation superpartners are singled out in several ways. First, their larger Yukawa couplings tend to drive the corresponding soft scalar masses smaller through the RGE evolution. Second, they play an important role in triggering radiative electroweak symmetry breaking, and as a result, fine-tuning arguments suggest that they are probably lighter than the other two generations<sup>1</sup> [1]. Finally, squark and slepton mixing for the third generation is typically rather large and further decreases the mass of the lightest mass eigenstates. For all of these reasons, it is possible that the third generation squarks and sleptons could be relatively light and therefore more easily accessible at the current and future colliders. Then, a logical thing to do will be to study particular signatures involving their decay products - top and bottom quarks, and tau leptons or neutrinos. Of these four, the tau leptons appear as the most promising possibility at the Tevatron. Tau neutrinos are invisible, and they often come paired with tau leptons anyway. Signatures with b-jets are also promising, but they tend to have large QCD backgrounds. And finally, top quarks are heavy, which limits the Tevatron reach for those channels.

Searches for supersymmetry (SUSY) in Run I of the Tevatron have been done exclusively in channels involving some combination of leptons, jets, photons and missing transverse energy ( $\cancel{E}_T$ ) [2]. At the same time, several Run I analyses have identified hadronic tau jets in the most abundant Standard Model processes, e.g. in  $W$ -production [3] and top decays [4]. Hadronically decaying taus have also been used to place limits on a charged Higgs [5] and leptoquarks [6]. Since tau identification is expected to improve further in Run II, this raises the question whether SUSY searches in channels involving tau jets are feasible.

SUSY signatures with tau leptons are very well motivated, since they arise in a variety of models of low-energy supersymmetry, e.g. gravity mediated (SUGRA) [7, 8, 9] or the minimal gauge mediated (MGM) models [9, 10, 11]. Here we present results from a study [12] of all possible *experimental* signatures with three identified objects (leptons or tau jets) plus  $\cancel{E}_T$ , and compare their reach to the clean trilepton channel [13, 14, 15, 7]. In evaluating the physics potential of the future Tevatron runs in these new tau channels, it is important

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<sup>1</sup>Notice, however, that unlike the first two generations, their masses are not so well restricted by the stringent constraints coming from flavor-changing processes.

to be aware not only of the physical backgrounds, but also of the experimental realities. Jets faking taus will comprise a significant fraction of the background, and it is crucial to have a reliable estimate of that rate, which we attempt to estimate from a detailed Monte Carlo analysis. We used PYTHIA [16] and TAUOLA [17] for event generation, and the SHW package [18], which provides a realistic Run II detector simulation.

In the next Section we delineate the relevant parameter space regions of the minimal SUGRA and MGM models, where one may expect enhanced tau signals. We then discuss in rather general terms the pros and cons of the tau jet channels. Later in Section 3 we describe in detail our analysis and present our cut selection. In Section 4 we discuss the major SM backgrounds, and in Section 5 we perform a study on triggering in those new channels. Finally in Section 6 we show the expected Run II Tevatron reach for the scenario under consideration.

## 2 Tau Signals in SUGRA and MGM Models

Most people would probably agree that our best bet to discover supersymmetry at the Tevatron is the clean  $3\ell \cancel{E}_T$  channel. It arises in the decays of gaugino-like chargino-neutralino pairs  $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ . The reach is somewhat limited by the rather small leptonic branching fractions of the chargino and neutralino. In the limit of either heavy or equal in mass squarks and sleptons, the leptonic branching ratios are  $W$ -like and  $Z$ -like, respectively. However, both gravity mediated and gauge mediated models of SUSY breaking allow the sleptons to be much lighter than the squarks, thus enhancing the leptonic branching fractions of the gauginos. What is more, in certain regions of parameter space the lightest tau slepton can be much lighter than the other sleptons, and then the gaugino decays will proceed predominantly to final states with tau leptons only.

### 2.1 Light sleptons

There are various generic reasons as to why one may expect light sleptons in the spectrum. For example, the slepton masses at the high-energy (GUT or messenger) scale may be rather small to begin with. This is typical for gauge mediated models, since the sleptons are colorless and do not receive large soft mass contributions  $\sim \alpha_s$ . The minimal SUGRA models, on the other hand, predict light sleptons in the region of parameter space where  $M_0 \ll M_{1/2}$ . Various effects (non-flat Kahler metric, RGE running above the GUT scale, D-terms from extra  $U(1)$  gauge factors) may induce nonuniversalities in the scalar masses

at the GUT scale, in which case the slepton-squark mass hierarchy can be affected. In the absence of a specific model, we do not know which way the splittings will go, but as long as the soft scalar masses are small, the RGE running down to the weak scale will naturally induce a splitting between the squarks and sleptons, making the sleptons lighter. Now, given that the sleptons are the lightest scalars in the spectrum, it is quite plausible that by far the lightest among them are the third generation sleptons. As we mentioned in Section 1, RGE running and mixing in the charged slepton sector may push the stau masses down.

As a result of some or all of these effects, it may very well be that among all scalars, only the lightest sleptons from each generation (or maybe just the lightest stau  $\tilde{\tau}_1$ ) are lighter than  $\tilde{\chi}_1^\pm$  and  $\tilde{\chi}_2^0$ . Indeed, in both SUGRA and minimal gauge mediated models one readily finds regions of parameter space where either

$$m_{\tilde{\chi}_1^0} < m_{\tilde{\tau}_1} \sim m_{\tilde{\mu}_R} < m_{\tilde{\chi}_1^+}$$

(typically at small  $\tan\beta$ ) or

$$m_{\tilde{\chi}_1^0} < m_{\tilde{\tau}_1} < m_{\tilde{\chi}_1^+} < m_{\tilde{\mu}_R}$$

(at large  $\tan\beta$ ). Depending on the particular model, and the values of the parameters, the gaugino pair decay chain may then end up overwhelmingly in *any one* of the four final states:  $\ell\ell\ell$ ,  $\ell\ell\tau$ ,  $\ell\tau\tau$  or  $\tau\tau\tau$ . (From now on, we shall use the following terminology: a “lepton” ( $\ell$ ) is either a muon or an electron; a tau ( $\tau$ ) is a tau-lepton, which can later decay either leptonically, or to a hadronic tau jet, which we denote by  $\tau_h$ ).

In Fig. 1 we show a scatter plot<sup>2</sup> of SUGRA model points plotted versus the ratios  $m_{\tilde{e}_R}/m_{\tilde{\chi}_1^0}$  and  $m_{\tilde{\tau}_1}/m_{\tilde{\chi}_1^0}$  (see [19] for details on how the sampling was done). We concentrate on the region  $M_0 \ll M_{1/2}$  and show only points with  $m_{\tilde{\tau}_1} < 3m_{\tilde{\chi}_1^0}$  and  $m_{\tilde{e}_R} < 3m_{\tilde{\chi}_1^0}$ . (Note that in SUGRA the lightest selectron or smuon is purely right-handed, while the lightest stau typically has a sizable left-handed component.) There are several distinct regions in relation to the branching ratios of the chargino-neutralino pair (recall that in SUGRA  $m_{\tilde{\chi}_1^+} \sim m_{\tilde{\chi}_2^0} \sim 2m_{\tilde{\chi}_1^0}$ ):

- Region I:  $m_{\tilde{e}_R} > m_{\tilde{\chi}_1^+}$  and  $m_{\tilde{\tau}_1} > m_{\tilde{\chi}_1^+}$ . In this case, all two-body decays are closed, and the leptonic branching ratios of the gauginos are  $W$ -like ( $Z$ -like).

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<sup>2</sup>Notice that the plots in this report are best viewed on a color screen, or when printed on a color printer.

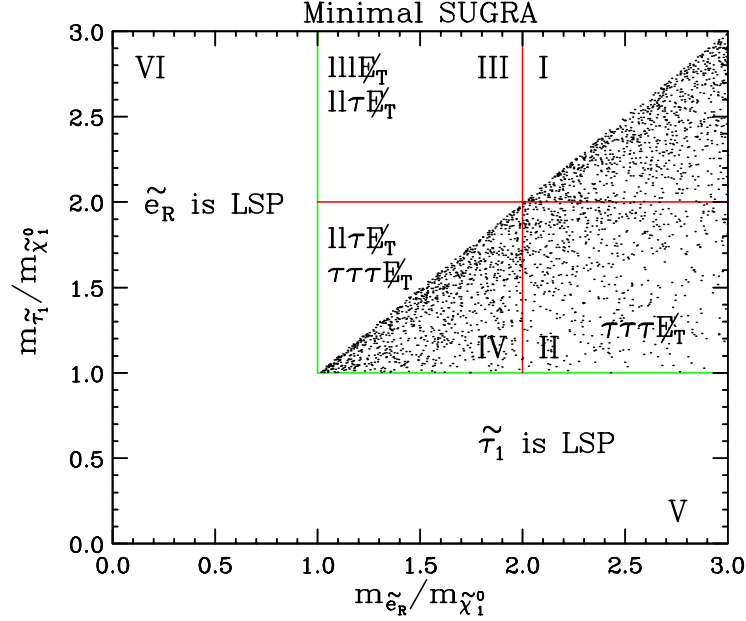


Figure 1: Scatter plot of minimal SUGRA model points versus the ratios  $m_{\tilde{e}_R}/m_{\tilde{\chi}_1^0}$  and  $m_{\tilde{\tau}_1}/m_{\tilde{\chi}_1^0}$ .

- Region II:  $m_{\tilde{e}_R} > m_{\tilde{\chi}_1^+}$ , but  $m_{\tilde{\chi}_1^0} < m_{\tilde{\tau}_1} < m_{\tilde{\chi}_1^+}$ , so that  $BR(\tilde{\chi}_1^+ \tilde{\chi}_2^0 \rightarrow \tau\tau\tau) \simeq 100\%$ . Note that if the stau mass is too close to either  $m_{\tilde{\chi}_1^0}$  or  $m_{\tilde{\chi}_1^+}$ , at least one of the resulting taus will be quite soft. One would therefore expect the largest efficiency if  $m_{\tilde{\tau}_1} \simeq (m_{\tilde{\chi}_1^+} + m_{\tilde{\chi}_1^0})/2$ .
- Region III:  $m_{\tilde{\tau}_1} > m_{\tilde{\chi}_1^+}$  and  $m_{\tilde{\chi}_1^0} < m_{\tilde{e}_R} < m_{\tilde{\chi}_1^+}$ . Then the gauginos can only decay to selectrons or smuons via two-body decays. Note that  $\tilde{\chi}_2^0$  is mostly  $\tilde{W}_3$ , while  $\tilde{\chi}_1^+$  is mostly  $\tilde{W}^+$ , and those do not couple to right-handed squarks or sleptons. Therefore the decay  $\tilde{\chi}_2^0 \rightarrow \tilde{\ell}^\pm \ell^\mp$  proceeds through the relatively small  $\tilde{B}$  component of the  $\tilde{\chi}_2^0$ , while the decay  $\tilde{\chi}_1^+ \rightarrow \tilde{\ell}^+ \nu_\ell$  is severely suppressed by the small muon or electron Yukawa couplings, and the three-body decays  $\tilde{\chi}_1^+ \rightarrow \tilde{\chi}_1^0 \ell^+ \nu_\ell$ ,  $\tilde{\chi}_1^+ \rightarrow \tilde{\chi}_1^0 \tau^+ \nu_\tau$  become dominant. Since those can also be mediated by an off-shell  $W$ , we expect both of them to be present. Notice how the assumption of generational independence of the scalar masses at the GUT scale assures that  $m_{\tilde{\tau}_1} < m_{\tilde{\ell}_R}$ , so that there are no SUGRA model points in region III, but this can be avoided if one allows for different stau and first two generation slepton masses at the GUT scale [20]<sup>3</sup>.

<sup>3</sup>Such a situation, however, is not well motivated from the point of view of SUSY GUTs. One can imagine that strict universality holds at the Planck scale, and then RGE running down to the GUT scale introduces intergenerational mass splittings. But then, due to the large tau Yukawa coupling, we would

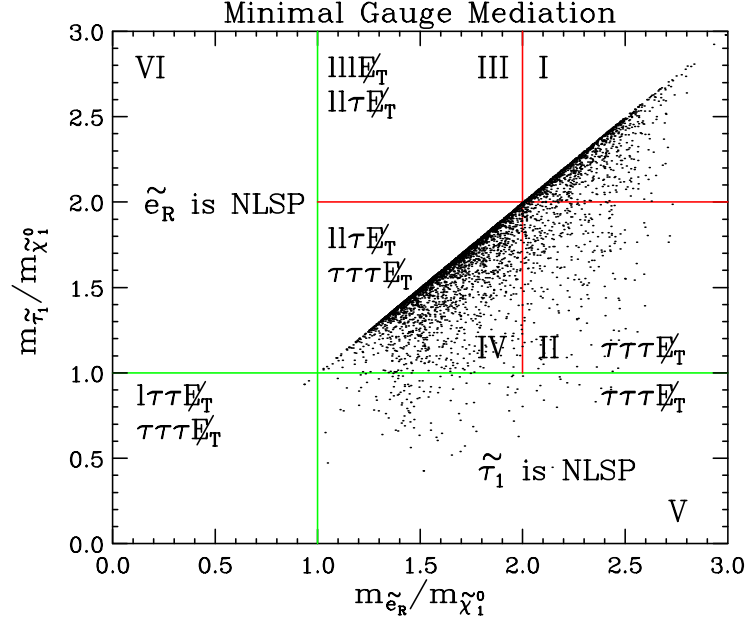


Figure 2: Scatter plot of MGM model points versus the ratios  $m_{\tilde{e}_R}/m_{\tilde{\chi}_1^0}$  and  $m_{\tilde{\tau}_1}/m_{\tilde{\chi}_1^0}$ .

- Region IV:  $m_{\tilde{\chi}_1^0} < m_{\tilde{e}_R} < m_{\tilde{\chi}_1^+}$  and  $m_{\tilde{\chi}_1^0} < m_{\tilde{\tau}_1} < m_{\tilde{\chi}_1^+}$ , so that the signatures from both regions II and III can be present. Now, the trilepton signal is somewhat suppressed, since the chargino decays mostly to taus.
- Region V:  $m_{\tilde{\tau}_1} < m_{\tilde{\chi}_1^0}$ . Here one finds a charged LSP (stau), which is stable, if R-parity is conserved, and therefore excluded cosmologically.
- Region VI:  $m_{\tilde{e}_R} < m_{\tilde{\chi}_1^0}$ . This region is excluded for the same reason as Region V, since now the smuon is the LSP.

To summarize, in SUGRA models, on most general grounds we expect chargino-neutralino pair production to give rise to  $\tau\tau\tau$ ,  $\tau\ell\ell$  or  $\ell\ell\ell$  final states, where the first two can be dominant in certain regions of parameter space.

We next consider the minimal gauge mediated models (we follow the conventions of Ref. [21]) and show the corresponding scatter plot in Fig. 2. Our discussion of regions I-IV above applies here as well. The novel feature is that now the goldstino  $\tilde{G}$  is the LSP, and therefore regions V and VI are in principle allowed. We do indeed find points in those regions, but only if  $m_{\tilde{e}_R} > m_{\tilde{\tau}_1}$ . This is again a consequence of the generation

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expect the tau slepton masses to be the lightest slepton masses at the GUT scale.



Experimental signature	Trilepton SUSY signal			
	$\tau\tau\tau$	$\tau\tau\ell$	$\tau\ell\ell$	$\ell\ell\ell$
$\tau_h\tau_h\tau_h$	0.268	—	—	—
$\ell\tau_h\tau_h$	0.443	0.416	—	—
$\ell\ell\tau_h$	0.244	0.458	0.645	—
$\ell\ell\ell$	0.045	0.126	0.355	1.00

Table 1: Branching ratios of the four possible SUSY signals into the corresponding experimental signatures involving final state leptons  $\ell$  (electrons or muons) as well as identified tau jets ( $\tau_h$ ).

independence of the scalar masses at the messenger scale, which is a robust prediction of the minimal gauge-mediated models. In order to avoid this argument, one would have to allow for messenger-matter mixing and arrange for different couplings of the messengers to the three families.

A very interesting situation may arise in the intersection of regions V and VI. If the mass splitting between  $\tilde{e}_R$ ,  $\tilde{\mu}_R$  and  $\tilde{\tau}_1$  is very small (i.e. at rather small values of  $\tan\beta$ ), they may all be co-NLSP's. Just as before,  $\tilde{\chi}_1^+$  will preferentially decay to taus:  $\tilde{\chi}_1^+ \rightarrow \tau\nu_\tau\tilde{G}$ . The neutralino decays, however, are of two sorts:  $\tilde{\chi}_i^0 \rightarrow \tilde{\tau}_1^\pm\tau^\mp \rightarrow \tau^\pm\tau^\mp\tilde{G}$  and  $\tilde{\chi}_i^0 \rightarrow \tilde{\ell}_R^\pm\ell^\mp \rightarrow \tilde{\tau}_1^\pm\ell^\mp X \rightarrow \tau^\pm\ell^\mp\tilde{G}X$ , where  $i = 1, 2$  and  $X$  stands for the very soft products of the selectron (or smuon) decay to a stau. The typical signature in this case would be  $\tau\tau\ell$ .

## 2.2 Tau Jets

The above discussion of the two most popular supersymmetric models reveals that, depending on the model parameters, the gaugino decay chains may overwhelmingly end up in any one of the four final states  $\tau\tau\tau$ ,  $\tau\tau\ell$ ,  $\tau\ell\ell$  and  $\ell\ell\ell$ . In order to decide as to which experimental signatures are most promising, we have to first factor in the tau branching ratios to leptons<sup>4</sup> and jets. About two-thirds of the subsequent tau decays are hadronic, so it appears advantageous to consider signatures with tau jets in the final state as alternatives to the clean trilepton signal. The branching ratios for three leptons or undecayed taus into a final state containing leptons and tau jets is shown in Table 1. We see that

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<sup>4</sup>Recall that here we call only the electrons and muons “leptons”, following experimentalists’ lingo.

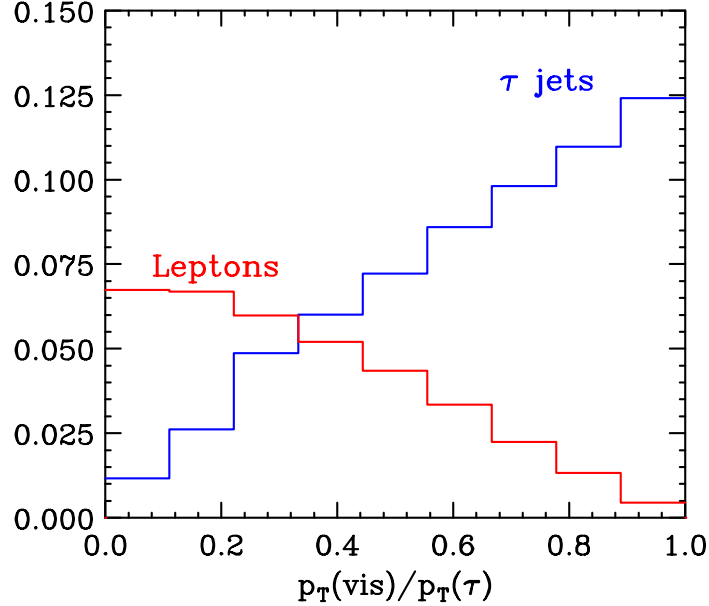


Figure 3: Distribution of the  $p_T$  fraction that the visible tau decay products (charged leptons or tau jets) inherit from the tau parent.

the presence of taus in the underlying SUSY signal always leads to an enhancement of the signatures with tau jets in comparison to the clean trileptons. This disparity is most striking for the case of  $\tau\tau\tau$  decays, where  $BR(\tau\tau\tau \rightarrow \ell\ell\tau_h)/BR(\tau\tau\tau \rightarrow \ell\ell\ell) \sim 5.5$ .

An additional advantage of the tau jet channels over the clean trileptons is that the leptons from tau decays are much softer than the tau jets and as a result will have a relatively low reconstruction efficiency. We illustrate this point in Fig. 3, where we show the distribution of the  $p_T$  fraction carried away by the visible decay products (charged lepton or tau jet) in tau decays (for theoretical discussions, see [22]). We can see that the leptons from tau decays are very soft, and it has been suggested [15] to use softer lepton  $p_T$  cuts in order to increase signal acceptance.

However, there are also some factors, which work against the tau jet channels. First and foremost, the background in those channels is larger than for the clean trileptons. The physical background (from *real* tau jets in the event) is actually smaller, but a significant part of the background is due to events containing narrow isolated QCD jets with the correct track multiplicity, which can be misidentified as taus. In Fig. 4 we show the tau fake rate that we obtained from SHW in  $W$  events. We define the fake rate as the number of QCD jets misidentified as taus over the total number of reconstructed QCD jets. The fake rate that we find with SHW is somewhat higher than in real data and/or with full

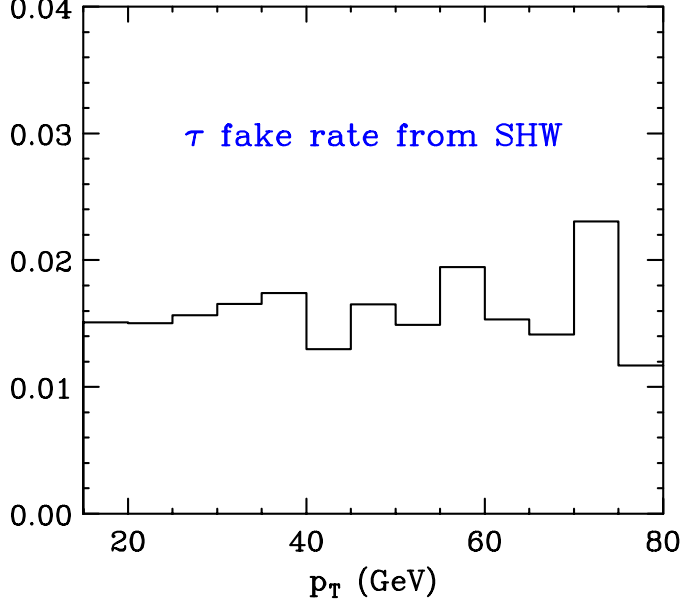


Figure 4: The tau fake rate defined as the number of QCD jets misidentified as taus over the total number of reconstructed QCD jets, in  $W$  events.

CDF detector simulation [23, 24]. This is to be expected in a much cleaner simulated environment, where, unlike real data, there is less junk flying around, and the jets tend to pass the isolation cuts more easily.

The jetty signatures are also hurt by the lower detector efficiency for tau jets than for leptons. The main goal of our study, therefore, was to see what would be the net effect of all these factors, on a channel by channel basis.

### 2.3 A Challenging Scenario

For our analysis we choose to examine one of the most challenging scenarios for SUSY discovery at the Tevatron. We assume the typical large  $\tan \beta$  mass hierarchy  $m_{\tilde{\chi}_1^0} < m_{\tilde{\tau}_1} < m_{\tilde{\chi}_1^+} < m_{\tilde{\mu}_R}$ . One then finds that  $BR(\tilde{\chi}_1^+ \tilde{\chi}_2^0 \rightarrow \tau\tau\tau + X) \simeq 100\%$  below  $\tilde{\chi}_1^\pm \rightarrow W^\pm \tilde{\chi}_1^0$  and  $\tilde{\chi}_2^0 \rightarrow Z \tilde{\chi}_1^0$  thresholds. In order to shy away from specific model dependence, we shall conservatively ignore all SUSY production channels other than  $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$  pair production. The  $p_T$  spectrum of the taus resulting from the chargino and neutralino decays depends on the mass differences  $m_{\tilde{\chi}_1^+} - m_{\tilde{\tau}_1}$  and  $m_{\tilde{\tau}_1} - m_{\tilde{\chi}_1^0}$ . The larger they are, the harder the spectrum, and the better the detector efficiency. However, as the mass difference gets large, the  $\tilde{\chi}_1^+$  and  $\tilde{\chi}_2^0$  masses themselves become large too, so the production cross-section is severely

suppressed. Therefore, at the Tevatron we can only explore regions with favorable mass ratios and at the same time small enough gaugino masses. This suggests a choice of SUSY mass ratios: for definiteness we fix  $2m_{\tilde{\chi}_1^0} \sim (4/3) m_{\tilde{\tau}_1} \sim m_{\tilde{\chi}_1^+} (< m_{\tilde{\mu}_R})$  throughout the analysis, and vary the chargino mass. The rest of the superpartners have fixed large masses corresponding to the mSUGRA point  $M_0 = 180$  GeV,  $M_{1/2} = 180$  GeV,  $A_0 = 0$  GeV,  $\tan\beta = 44$  and  $\mu > 0$ , but we are not constrained to mSUGRA models only. Our analysis will apply equally to gauge-mediated models with a long-lived neutralino NLSP, as long as the relevant gaugino and slepton mass relations are similar. Note that our choice of heavy first two generation sleptons is very conservative. A more judicious choice of their masses, namely  $m_{\tilde{\mu}_R} < m_{\tilde{\chi}_1^+}$ , would lead to a larger fraction of trilepton events, and as a result, a higher reach. Furthermore, the gauginos would then decay via two-body modes to first generation sleptons, and the resulting lepton spectrum would be much harder, leading to a higher lepton efficiency. Notice also that the  $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$  production cross-section is sensitive to the squark masses, but since this is the only production process we are considering, our results can be trivially rescaled to account for a different choice of squark masses, or to include other production processes as well.

### 3 Analysis

We used PYTHIA v6.115 and TAUOLA v2.5 for event generation. We used the SHW v2.2 detector simulation package [18], which simulates an average of the CDF and D0 Run II detector performance. In SHW tau objects are defined as jets with  $|\eta| < 1.5$ , net charge  $\pm 1$ , one or three tracks in a  $10^\circ$  cone with no additional tracks in a  $30^\circ$  cone,  $E_T > 5$  GeV,  $p_T > 5$  GeV, plus an electron rejection cut. SHW electrons are required to have  $|\eta| < 1.5$ ,  $E_T > 5$  GeV, hadronic to electromagnetic energy deposit ratio  $R_{h/e} < 0.125$ , and satisfy standard isolation cuts. Muon objects are required to have  $|\eta| < 1.5$ ,  $E_T > 3$  GeV and are reconstructed using Run I efficiencies. We use standard isolation cuts for muons as well. Jets are required to have  $|\eta| < 4$ ,  $E_T > 15$  GeV. In addition we have added jet energy correction for muons and the rather loose id requirement  $R_{h/e} > 0.1$ . We have also modified the TAUOLA program in order to correctly account for the chirality of tau leptons coming from SUSY decays.

The reconstruction algorithms in SHW already include some basic cuts, so we can define a reconstruction efficiency  $\epsilon_{rec}$  for the various types of objects: electrons, muons, tau jets etc. We find that as we vary the chargino mass from 100 to 140 GeV the lepton

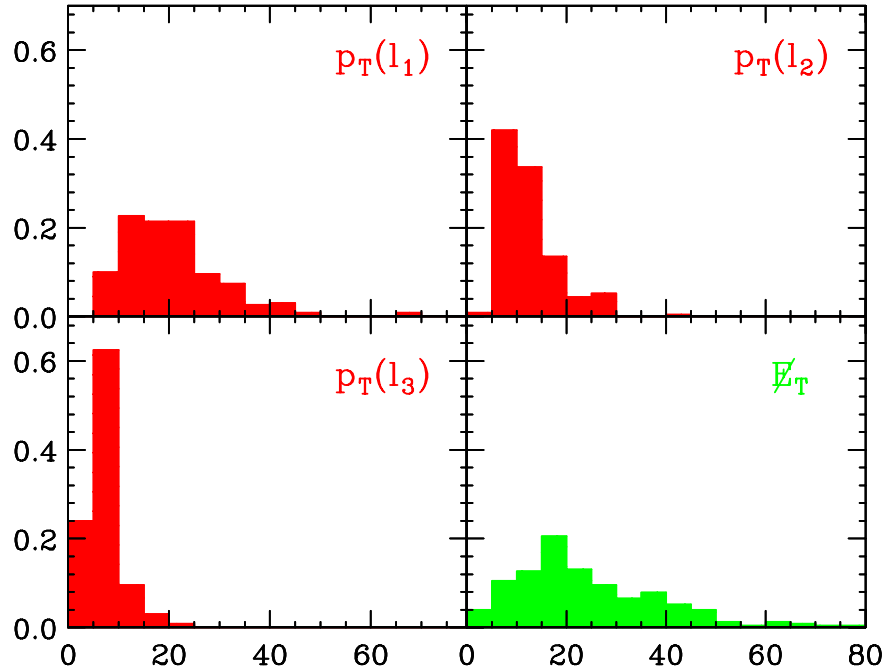


Figure 5:  $p_T$  distributions of the three leptons and  $E_T$  distribution (all normalized to unit probability) in  $\ell\ell\ell\cancel{E}_T$  signal events, for  $m_{\tilde{\chi}_1^+} = 123$  GeV.

and tau jet reconstruction efficiencies for the signal range from 42 to 49 %, and from 29 to 36%, correspondingly. The lepton efficiency may seem surprisingly low, but this is because a lot of the leptons are very soft and fail the  $E_T$  cut. The tau efficiency is in good agreement with the results from Ref. [23] and [24], once we account for the different environment, as well as cuts used in those analyses.

As we already emphasized earlier, the most important background issue in the new tau channels is the fake tau rate. Several experimental analyses try to estimate it using Run I data. Here we simulate the corresponding backgrounds to our signal and use SHW to obtain the fake rate, thus avoiding trigger bias [23].

### 3.1 Cuts

We now list our cuts for each channel.

As discussed earlier, we expect that the reach in the classic  $\ell\ell\ell\cancel{E}_T$  channel will be quite suppressed, due to the softness of the leptons (we show the  $p_T$  distribution of the three leptons, as well as the  $E_T$  distribution, in Fig. 5). Therefore we apply the soft cuts

Sample	$\cancel{E}_T$ cut	Jet veto
A	20 GeV	no
B	25 GeV	no
C	20 GeV	yes
D	25 GeV	yes

Table 2: Definition of the signal samples A-D.

advertised in Refs. [15]. We require a central lepton with  $p_T > 11$  GeV and  $|\eta| < 1.0$ , and in addition two more leptons with  $p_T > 7$  GeV and  $p_T > 5$  GeV. Leptons have to be isolated:  $I(\ell) < 2$  GeV, where  $I$  is the total transverse energy contained in a cone of size  $\delta R = \sqrt{\Delta\varphi^2 + \Delta\eta^2} = 0.4$  around the lepton. We impose a dilepton invariant mass cut for same flavor, opposite sign leptons:  $|m_{\ell+\ell-} - M_Z| > 10$  GeV and  $|m_{\ell+\ell-}| > 11$ . Finally, we impose an optional veto on additional jets and require  $\cancel{E}_T$  to be either more than 20 GeV, or 25 GeV. This gives us a total of four combinations of the  $\cancel{E}_T$  cut and the jet veto (shown in Table 2), which we apply for all tau jet signatures later as well.

For our  $\ell\ell\tau_h \cancel{E}_T$  analysis we impose cuts similar to the stop search analysis in the  $\ell^+\ell^-j \cancel{E}_T$  channel [25]: two isolated ( $I(\ell) < 2$  GeV) leptons with  $p_T > 8$  GeV and  $p_T > 5$  GeV, and one identified tau jet with  $p_T(\tau_h) > 15$  GeV (the  $p_T$  and  $\cancel{E}_T$  distributions are shown in Fig. 6). Again, we impose the above invariant mass cuts for any same flavor, opposite sign dilepton pair. This channel was previously considered in Ref. [8], but with somewhat harder cuts on the leptons.

A separate, very interesting signature ( $\ell^+\ell^+\tau_h \cancel{E}_T$ ) arises if the two leptons have the same sign, since the background is greatly suppressed. In fact, we expect this background to be significantly smaller than the trilepton background! Roughly one third of the signal events in the general  $\ell\ell\tau_h$  sample are expected to have like-sign leptons.

For our  $\ell\tau_h\tau_h \cancel{E}_T$  analysis we use some basic identification cuts: two tau jets with  $p_T > 15$  GeV and  $p_T > 10$  GeV and one isolated lepton with  $p_T > 7$  GeV. The corresponding  $p_T$  and  $\cancel{E}_T$  distributions are shown in Fig. 7.

Finally, for the  $\tau_h\tau_h\tau_h \cancel{E}_T$  signature we only require three tau jets with  $p_T > 15, 10$  and 8 GeV, respectively (Fig. 8).

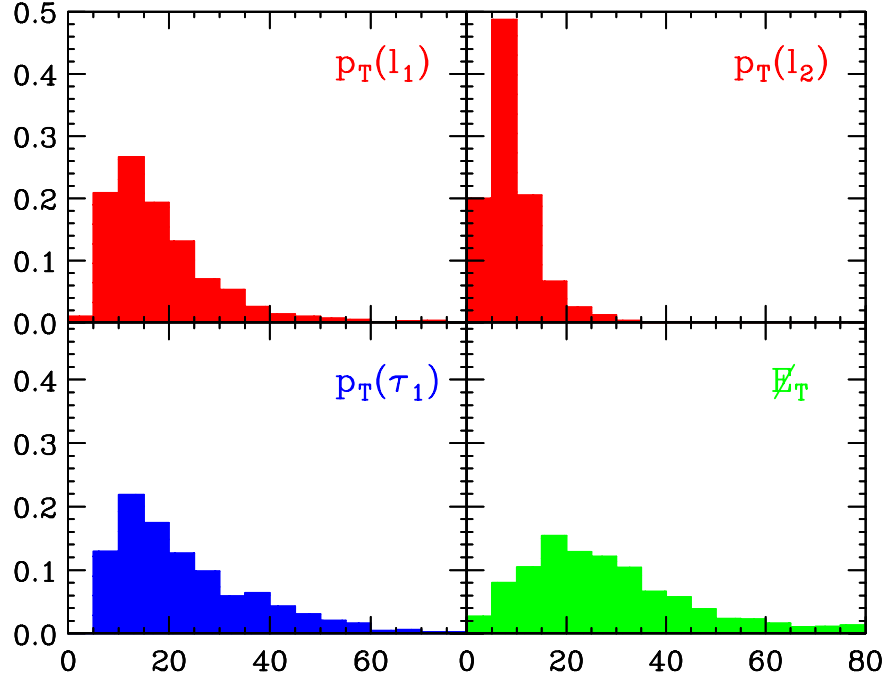


Figure 6: The same as Fig. 5, but for the two leptons and the tau jet in  $\ell\ell\tau_h \cancel{E}_T$  signal events.

### 3.2 Signal

One can get a good idea of the relative importance of the different channels by looking at the corresponding signal samples after the analysis cuts have been applied. In Fig. 9 we show the signal cross-sections times the corresponding branching ratios times the total efficiency  $\epsilon_{tot} \equiv \epsilon_{rec}\epsilon_{cuts}$ , which accounts for both the detector acceptance  $\epsilon_{rec}$  and the efficiency of the cuts  $\epsilon_{cuts}$  (for each signal point we generated  $10^5$  events). We see that the lines are roughly ordered according to the branching ratios from Table 1. This can be understood as follows. The acceptance (which includes the basic ID cuts in SHW) is higher for leptons than for  $\tau$  jets. Therefore, replacing a lepton with a tau jet in the experimental signature costs us a factor of  $\sim 1.5$  in acceptance, due to the poorer reconstruction of tau jets, compared to leptons. Later, however, the cuts tend to reduce the leptonic signal more than the tau jet signal. This is mostly because the leptons are softer than the tau jets. Notice that we cannot improve the efficiency for leptons by further lowering the cuts – we are already using the most liberal cuts [15]. It turns out that these two effects mostly cancel each other, and the total efficiency  $\epsilon_{tot}$  is roughly the

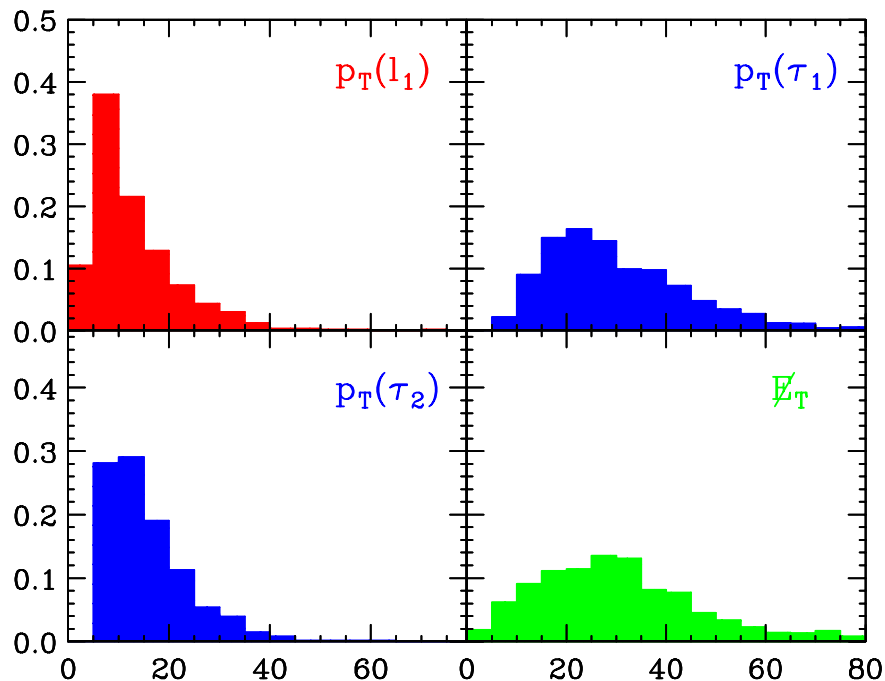


Figure 7: The same as Fig. 5, but for the lepton and the two tau jets in  $\ell\tau_h\tau_h\cancel{E}_T$  signal events.

same for all channels. Therefore the relative importance of each channel will only depend on the tau branching ratios and the backgrounds. For example, in going from  $\ell\ell\ell$  to  $\ell\ell\tau_h$ , one wins a factor of 5.5 from the branching ratio. Therefore the background to  $\ell\tau_h\tau_h\cancel{E}_T$  must be at least  $5.5^2 \sim 30$  times larger in order for the clean trilepton channel to be still preferred.

## 4 Backgrounds

We next turn to the discussion of the backgrounds involved. We have simulated the following physics background processes:  $ZZ$ ,  $WZ$ ,  $WW$ ,  $t\bar{t}$ ,  $Z + jets$ , and  $W + jets$ , generating  $10^6$ ,  $10^6$ ,  $10^6$ ,  $10^6$ ,  $10^7$  and  $10^7$  events, respectively. We list the results in Tables 3-6, where all errors are purely statistical. A few comments are in order.

1.  $WZ$  is indeed the major source of background for the trilepton channel. The majority of the background events contain a leptonically decaying off-shell  $Z$  and pass the invariant dilepton mass cut. The rest of the  $WZ$  background comes from



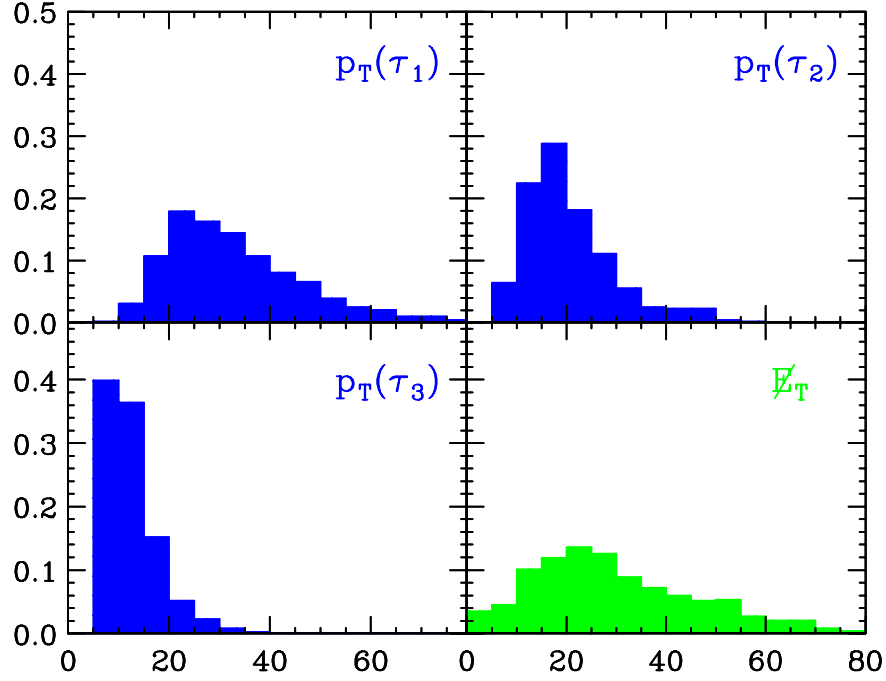


Figure 8: The same as Fig. 5, but for the tau jets in  $\tau_h \tau_h \tau_h \cancel{E}_T$  signal events.

	Experimental signatures				
	$\ell\ell\ell\cancel{E}_T$	$\ell\ell\tau_h\cancel{E}_T$	$\ell^+\ell^+\tau_h\cancel{E}_T$	$\ell\tau_h\tau_h\cancel{E}_T$	$\tau_h\tau_h\tau_h\cancel{E}_T$
$ZZ$	$0.196 \pm 0.028$	$0.334 \pm 0.036$	$0.094 \pm 0.019$	$0.181 \pm 0.027$	$0.098 \pm 0.020$
$WZ$	$1.058 \pm 0.052$	$1.087 \pm 0.053$	$0.447 \pm 0.034$	$1.006 \pm 0.051$	$0.248 \pm 0.025$
$WW$	—	$0.416 \pm 0.061$	—	$0.681 \pm 0.078$	$0.177 \pm 0.039$
$t\bar{t}$	$0.300 \pm 0.057$	$1.543 \pm 0.128$	$0.139 \pm 0.038$	$1.039 \pm 0.105$	$0.161 \pm 0.041$
$Zj$	$0.112 \pm 0.079$	$7.34 \pm 0.64$	$0.168 \pm 0.097$	$20.3 \pm 1.1$	$17.9 \pm 1.0$
$Wj$	—	—	—	$37.2 \pm 2.9$	$6.1 \pm 1.2$
$\sigma_{BG}^{\text{tot}}$	$1.67 \pm 0.11$	$10.7 \pm 0.7$	$0.85 \pm 0.11$	$60.4 \pm 3.1$	$24.7 \pm 1.6$

Table 3: Results for the individual SM backgrounds (in fb), as well as the total background  $\sigma_{BG}^{\text{tot}}$  in the various channels for case A:  $\cancel{E}_T > 20$  GeV and no jet veto.

$Z \rightarrow \tau^+\tau^- \rightarrow \ell^+\ell^- \cancel{E}_T$ . The  $WZ$  rate then is a factor of three higher than in recent tripleton analyses prior to the SUSY/Higgs workshop (see, e.g. [7, 8, 15]).

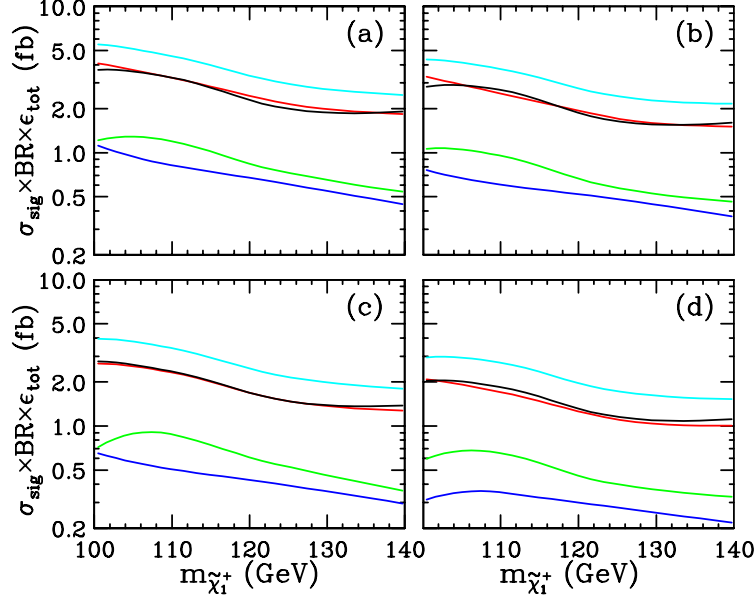


Figure 9: Signal cross-section times branching ratio after cuts for the five channels discussed in the text:  $\ell\ell\ell E_T$  (blue),  $\ell\ell\tau_h E_T$  (red),  $\ell^+\ell^+\tau_h E_T$  (green),  $\ell\tau_h\tau_h E_T$  (cyan) and  $\tau_h\tau_h\tau_h E_T$  (black); and for various sets of cuts: (a) cuts A, (b) cuts B, (c) cuts C and (d) cuts D.

	Experimental signatures				
	$\ell\ell\ell E_T$	$\ell\ell\tau_h E_T$	$\ell^+\ell^+\tau_h E_T$	$\ell\tau_h\tau_h E_T$	$\tau_h\tau_h\tau_h E_T$
$ZZ$	$0.165 \pm 0.025$	$0.271 \pm 0.033$	$0.090 \pm 0.019$	$0.153 \pm 0.024$	$0.086 \pm 0.018$
$WZ$	$0.964 \pm 0.050$	$1.001 \pm 0.051$	$0.423 \pm 0.033$	$0.909 \pm 0.049$	$0.204 \pm 0.023$
$WW$	—	$0.380 \pm 0.058$	—	$0.602 \pm 0.073$	$0.142 \pm 0.036$
$t\bar{t}$	$0.300 \pm 0.057$	$1.500 \pm 0.127$	$0.139 \pm 0.038$	$0.996 \pm 0.103$	$0.128 \pm 0.037$
$Zj$	$0.056 \pm 0.056$	$4.87 \pm 0.52$	$0.112 \pm 0.079$	$13.61 \pm 0.87$	$11.82 \pm 0.81$
$Wj$	—	—	—	$32.1 \pm 2.7$	$5.5 \pm 1.1$
$\sigma_{BG}^{\text{tot}}$	$1.49 \pm 0.10$	$8.0 \pm 0.5$	$0.76 \pm 0.09$	$48.4 \pm 2.8$	$17.9 \pm 1.4$

Table 4: The same as Table 3, but for case B.

To simulate the diboson backgrounds, most previous estimates employed ISAJET, where the  $W$  and  $Z$  gauge bosons are always generated exactly on their mass shell,

	Experimental signatures				
	$\ell\ell E_T$	$\ell\ell\tau_h E_T$	$\ell^+\ell^+\tau_h E_T$	$\ell\tau_h\tau_h E_T$	$\tau_h\tau_h\tau_h E_T$
$ZZ$	$0.114 \pm 0.021$	$0.220 \pm 0.029$	$0.071 \pm 0.017$	$0.094 \pm 0.019$	$0.031 \pm 0.011$
$WZ$	$0.805 \pm 0.046$	$0.828 \pm 0.046$	$0.347 \pm 0.030$	$0.695 \pm 0.043$	$0.136 \pm 0.019$
$WW$	—	$0.301 \pm 0.052$	—	$0.354 \pm 0.056$	$0.097 \pm 0.029$
$t\bar{t}$	—	$0.086 \pm 0.030$	—	$0.032 \pm 0.018$	—
$Zj$	$0.056 \pm 0.056$	$4.93 \pm 0.52$	$0.056 \pm 0.056$	$12.66 \pm 0.84$	$10.36 \pm 0.76$
$Wj$	—	—	—	$25.8 \pm 2.4$	$3.2 \pm 0.9$
$\sigma_{BG}^{\text{tot}}$	$0.97 \pm 0.07$	$6.4 \pm 0.5$	$0.47 \pm 0.06$	$39.6 \pm 2.5$	$13.8 \pm 1.2$

Table 5: The same as Table 3, but for case C.

	Experimental signatures				
	$\ell\ell\ell E_T$	$\ell\ell\tau_h E_T$	$\ell^+\ell^+\tau_h E_T$	$\ell\tau_h\tau_h E_T$	$\tau_h\tau_h\tau_h E_T$
$ZZ$	$0.098 \pm 0.020$	$0.177 \pm 0.026$	$0.071 \pm 0.017$	$0.075 \pm 0.017$	$0.027 \pm 0.010$
$WZ$	$0.732 \pm 0.044$	$0.766 \pm 0.045$	$0.329 \pm 0.029$	$0.622 \pm 0.040$	$0.115 \pm 0.017$
$WW$	—	$0.274 \pm 0.049$	—	$0.327 \pm 0.054$	$0.071 \pm 0.025$
$t\bar{t}$	—	$0.075 \pm 0.028$	—	$0.032 \pm 0.018$	—
$Zj$	—	$3.25 \pm 0.24$	—	$7.62 \pm 0.65$	$6.55 \pm 0.61$
$Wj$	—	—	—	$22.6 \pm 2.3$	$3.0 \pm 0.8$
$\sigma_{BG}^{\text{tot}}$	$0.83 \pm 0.05$	$4.5 \pm 0.3$	$0.40 \pm 0.03$	$31.3 \pm 2.4$	$9.8 \pm 1.0$

Table 6: The same as Table 3, but for case D.

and there is no finite-width smearing effect [26], [27] <sup>5</sup>.

2. As we move to channels with more tau jets, the number of background events with *real* tau jets decreases: first, because of the smaller branching ratios of  $W$  and  $Z$

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<sup>5</sup>Since then, the trilepton analysis has been redone independently by several groups and the increase in the  $WZ$  background has been confirmed [26, 27, 28, 29, 30, 31, 32]. In addition, the virtual photon contribution and the  $Z-\gamma$  interference effect, neither of which is modelled in either PYTHIA or ISAJET, have also been included [28, 29, 30, 31, 32], which further increases the background several times. This required new cuts, specifically designed to remove these additional contributions [29, 31].

to taus; and second, because the tau jets in  $W$  and  $Z$  decays are *softer* than the leptons from  $W$  and  $Z$ . This is to be contrasted with the signal, where, conversely, the tau jets are harder than the leptons. We also see, however, that the contribution from events with fake taus (from hadronically decaying  $W$ 's and  $Z$ 's or from initial and final state jet radiation) increases, and for the  $3\tau$  channel events with fake taus are the dominant part of the  $WZ$  background.

3. Notice that the  $WZ$  background to the same-sign dilepton channel is smaller (by a factor of two) than for the trilepton channel. As expected, it is also about a half of the total contribution to  $\ell\ell\tau$  (recall that for the signal this ratio is only a third). Indeed, one third of the events with opposite sign leptons come from the  $Z$ -decay and are cut away by the dilepton mass cut.
4. Vetoing a fourth lepton in the event reduces the  $ZZ$  background to the trilepton channel only by 4–8 %. The  $ZZ$  trilepton background is due to one  $Z$  decaying as  $Z \rightarrow \tau\tau$ , thus providing the missing energy in the event, and the other  $Z$  decaying to leptons:  $Z \rightarrow \ell^+\ell^-$ . Most of the events passing the cuts contain an off-shell  $Z/\gamma$  decaying leptonically<sup>6</sup>, and the third lepton coming from a leptonic tau. But then it is 6 times more probable that the second tau would decay hadronically and will not give a fourth lepton. The rest of the  $ZZ$  background events come from a regular  $Z \rightarrow \ell^+\ell^-$  decay, where one of the leptons is missed, and the invariant mass cut does not apply. For those events, there is obviously no fourth lepton.
5. The jet veto is very effective in reducing the  $t\bar{t}$  background for the first three channels. However, it also reduces the signal (see Fig. 9).
6. In all channels, a higher  $\cancel{E}_T$  cut did not help to get rid of the major backgrounds. Indeed,  $WZ$ ,  $t\bar{t}$  and/or  $Wj$  backgrounds tend to have a lot of missing energy, due to the leptonic  $W$ -decays.
7. Our result for the  $Wj$  and  $Zj$  backgrounds should be taken with a grain of salt, in spite of the relatively small statistical errors. Events with fake leptons are expected to comprise a major part of this background, and SHW does not provide a realistic simulation of those. In fact, the most reliable way to estimate this background will be from Run IIa data, e.g. by estimating the probability for an isolated track from

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<sup>6</sup>ISAJET analyses are missing this component of the  $ZZ$  background.

Drell-Yan events, and the lepton fake rate per isolated track from minimum bias data [33, 27, 29].

8. We have underestimated the total background to the three-jet channel by considering only processes with at least one real tau in the event. We expect sizable contributions from pure QCD multijet events, or  $Wj \rightarrow jjj$ , where *all* three tau jets are fake.

## 5 Triggers

Since the four experimental signatures in our analysis contain only soft leptons and tau jets, an important issue is whether one can develop efficient combinations of Level 1 and Level 2 triggers to accumulate these data sets without squandering all of the available bandwidth. A dedicated low  $p_T$  tau trigger for Run II, which may be suitable for the new tau jet channels, is now being considered by CDF [34].

In order to get an idea how well we can trigger on these new channels in Run II, we made use of the existing trigger objects in the SHW package. Until the design and approval of a dedicated tau trigger, which will collect most of the signal sample by itself, we want to make sure that the signal events will somehow end up on tape with the already existing triggers and will not be lost. This is why we considered a standard set of triggers used for SUSY analyses at the Tevatron [7, 8]. Of the five triggers used in [7, 8] we discarded the multijet trigger as not useful for our channels, and the dilepton plus  $\cancel{E}_T$  trigger as unrealistic for Run II. We then conservatively tightened the thresholds of the  $\cancel{E}_T$  trigger and the single lepton trigger:

1.  $\cancel{E}_T > 40$  GeV;
2.  $p_T(\ell) > 20$  GeV;
3.  $p_T(\ell) > 10$  GeV,  $p_T(j) > 15$  GeV and  $\cancel{E}_T > 15$  GeV,

and counted how many of the signal events *after cuts* were collected by these three triggers. The results are shown in Table 7. We can see that across the board the three very simplified triggers did a very good job and typically picked up about 90% of the signal events which contained at least one lepton.

We also checked if we can use the tau trigger in SHW (which is calorimetry-based and probably not the most suitable trigger for our purposes [34]) to collect some of the

$m_{\tilde{\chi}_1^\pm}$ (GeV)	$\ell\ell\ell \cancel{E}_T$	$\ell\ell\tau \cancel{E}_T$	$\ell\tau\tau \cancel{E}_T$	$\tau\tau\tau \cancel{E}_T$
100	82%	94%	83%	50%
110	85%	93%	83%	52%
123	95%	91%	86%	55%
140	93%	95%	89%	60%

Table 7: Fraction of signal events *after cuts* collected by the set of three triggers described in the text.

remaining events. We considered the effect of a mixed  $\ell + \tau$  trigger and found only some marginal improvement of a few percent. The only case, in which a new trigger helps a lot is the jetty channel  $\tau_h\tau_h\tau_h$ , where it is a  $\tau - \tau$  and not  $\ell - \tau$  trigger which is relevant. However, developing a stand-alone hadronic double tau trigger does not seem well justified – the fake rate for QCD jets faking taus is large enough to make the trigger fire mostly on pure QCD events, where two jets are faking taus. In order to even entertain the idea of a double tau trigger, one would have to think seriously about adding an extra requirement, for example  $\cancel{E}_T$ , but then the trigger becomes too complicated. Besides, it helps a lot only for the channel with the worst reach (and largest backgrounds). It may in fact be a better idea to lower the threshold of the  $\cancel{E}_T$  trigger instead.

## 6 Tevatron Reach

A  $3\sigma$  exclusion limit would require a total integrated luminosity

$$L = \frac{9\sigma_{BG}}{\left(\sigma_{sig} BR(\tilde{\chi}_1^+ \tilde{\chi}_2^0 \rightarrow X) \epsilon_{tot}\right)^2}. \quad (1)$$

Notice that  $L(3\sigma)$  depends linearly on the background  $\sigma_{BG}$  after cuts, but *quadratically* on the signal branching ratios. This allows the jetty channels to compete very successfully with the clean trilepton signature, whose branching ratio is quite small (see Table 1). In Fig. 10 we show the Tevatron reach in the three channels: trileptons (blue), dileptons plus a tau jet (red) and like-sign dileptons plus a tau jet (green). We see that the two channels with tau jets have a much better sensitivity compared to the usual trilepton signature. Assuming that efficient triggers can be implemented, the Tevatron reach will start exceeding LEP II limits as soon as Run IIa is completed and the two collaborations

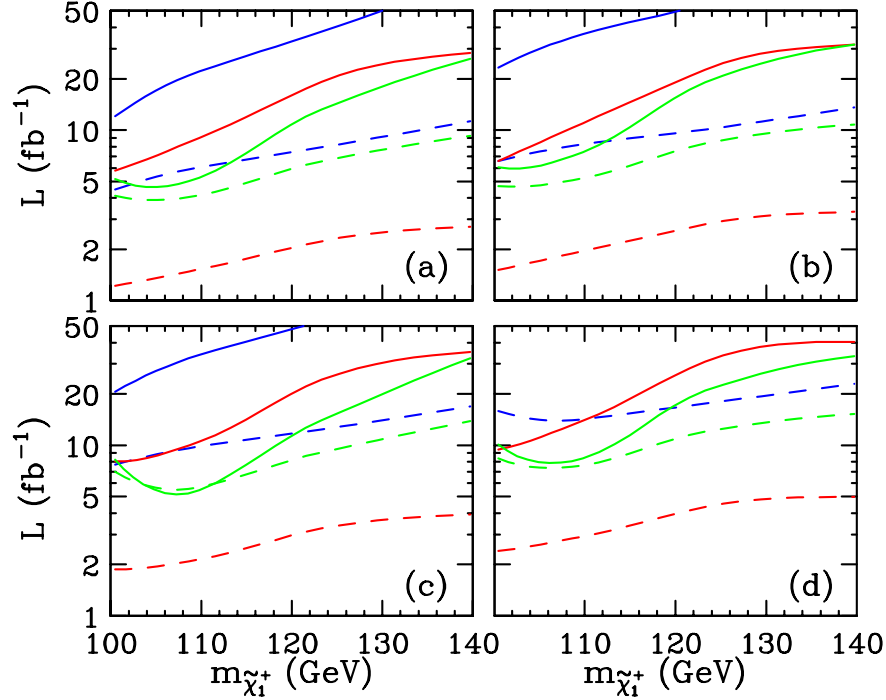


Figure 10: The total integrated luminosity  $L$  needed for a  $3\sigma$  exclusion (solid lines) or observation of 5 signal events (dashed lines), as a function of the chargino mass  $m_{\tilde{\chi}_1^+}$ , for the three channels:  $\ell\ell\ell \cancel{E}_T$  (blue),  $\ell\ell\tau_h \cancel{E}_T$  (red) and  $\ell^+\ell^+\tau_h \cancel{E}_T$  (green); and for various sets of cuts: (a) cuts A; (b) cuts B; (c) cuts C and (d) cuts D.

have collected a total of  $4 \text{ fb}^{-1}$  of data. Considering the intrinsic difficulty of the SUSY scenario we are contemplating, the mass reach for Run IIb is quite impressive. One should also keep in mind that we did not attempt to optimize our cuts for the new channels. For example, one could use angular correlation cuts to suppress Drell-Yan, transverse  $W$  mass cut to suppress  $WZ$  [31], or (chargino) mass-dependent  $p_T$  cuts for the leptons and tau jets [27, 29], to squeeze out some extra reach. In addition, the  $\ell\ell\tau_h$  channel can be explored at smaller values of  $\tan\beta$  as well [8, 15, 27, 29], since the two-body chargino decays are preferentially to tau sleptons. In that case, the clean trilepton channel still offers the best reach, and a signal can be observed already in Run IIa. Then, the tau channels will not only provide an important confirmation, but also hint towards some probable values of the SUSY model parameters.

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